



Archaeobotanical implications of phytolith assemblages from cultivated rice systems, wild rice stands and macro-regional patterns[☆]



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ABSTRACT

Rice can be cultivated in a range of arable systems, including upland rainfed, lowland rainfed or irrigated, flooded or *décrue*, and deep water cultivation. These agricultural regimes represent ecosystems controlled to large degree by agricultural practices, and can be shown to produce different weed flora assemblages. In order to reconstruct early rice cultivation systems it is necessary to better establish how ancient rice farming practices may be seen using archaeobotanical data. This paper focuses on using modern analogue phytolith assemblages of associated crop weeds found within cultivation regimes, as well as in wild rice stands (unplanted stands of *Oryza nivara* or *Oryza rufipogon*), as a means of interpreting archaeobotanical assemblages. Rice weeds and sediment samples have been recorded and collected from a range of arable systems and wild stands in India. The husks, leaves and culms of associated weeds were processed for phytolith reference samples, and sediment samples were processed for phytoliths in order to establish patterns identifiable to specific systems. The preliminary results of the phytolith analysis of samples from these modern fields demonstrate that phytolith assemblage statistics show correlation with variation in rice cultivation systems on the basis of differences in environmental conditions and regimes, with wetness being one major factor. Analysis of phytoliths from archaeological samples from contrasting systems in Neolithic China and India demonstrate how this method can be applied to separate archaeological regions and periods based on inferred differences in past agricultural practices, identifying wet cultivation systems in China, dry millet-dominated agriculture of north China and rainfed/dry rice in Neolithic India.

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1. Introduction

Rice has provided the dietary staple for a large proportion of the world's population since the earliest civilizations in Southern China, Southeast Asia and large parts of India and Sri Lanka (Fuller et al., 2010; Castillo and Fuller, 2010). Understanding how rice production systems evolved and intensified is therefore fundamental to the archaeology of early civilizations in monsoonal Asia (Gourou, 1984; Bray, 1994; Glover and Higham, 1996). When and how rice farming began, and the nature of its early impact on the landscape and demands on human labour, are key issues in the long-term history of Asia. Because rice can be grown across a wide

range of ecological systems from those with intensively managed water resources to less labour-demanding rainfed systems, there is scope for moving beyond simply recording the presence or absence of rice in the past (Fuller and Qin, 2009; Fuller et al., 2011a). Based on existing data for the distribution of rice we have produced preliminary models for the expansion of land area exploited for wet versus dry rice, and have estimated plausible methane output levels from wet rice over time (Fuller et al., 2011a). However, one of the weaknesses in existing data is that archaeological evidence for how rice was cultivated, in wet or dry systems, is extremely scarce. Therefore, one of our major aims has been to develop new systematic methods for inferring how rice was cultivated in the past (Fuller and Weisskopf, 2011). The statistical analysis of archaeological phytolith (biogenic silica) assemblages provides one approach, and we report results here from analyses of modern analogue soil phytoliths and some archaeological assemblages.

Rice typically grows in two contrasting micro niches or ecotypes; wet systems with standing water for much of the growth

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cycle, found in lowland irrigated paddies and terraced systems, and upland rainfed dry fields, including some shifting cultivation systems (Fig. 1). While the cultivation methods differ, many varieties will grow in either niche, and the morphology of archaeological rice remains will not be diagnostic of the how rice was cultivated. As discussed elsewhere, the differing ecologies of annual and perennial wild rices suggest two different ecologies of early rice exploitation and cultivation, one focused in perennial wetlands and the other seasonal fluctuating monsoonal wetlands (Fuller and Qin, 2009; Fuller et al., 2010). As rice agriculture emerged and spread, people began to manage these wetland niches, often through the control of water (Barnes, 1990). Within rice cultivation systems, the hydrological regime can be divided into five major categories (Fig. 1; and see Jacquot and Courtois, 1987; Khush, 1997: 31; Mathews et al., 1995:100–1; Fuller et al., 2011a). In addition, upland terraced systems represent an extreme form of landscape modification that allows the extension of irrigated rice to higher elevations. Systems of rice cultivation have been classified in other ways, such as in terms of how rice is sown and grown, e.g. shifting cultivation, broadcast sown fields or transplanted rice seedlings from nursery beds (Hanks, 1972; Watabe, 1967). These techniques, especially broadcasting, may cut across different ecosystems, but they may also affect the weed flora present in the fields (e.g. Nantasomsaran and Moody, 1995). Based on ethnohistoric observations in West Africa, *décrué* agriculture can be defined as a low-labour input system of broadcasting seeds into a flooded alluvial sedimentary setting after the flood has receded (Harlan and Pasquereau, 1969). All of these rice growing habitats differ to varying degrees in weed taxa, and it is our contention that phytolith assemblages may pick out different floras of weeds and thus be used to distinguish these different cultivation systems. The examination of different fossil proxies for weed floras from archaeobotanical contexts as a means of inferring cultivation practices has been previously established as a workable method in Europe and the Near East (Charles et al., 2003; Jones et al., 2005; Bogaard et al., 2005), and has also been used to distinguish early cultivation from wild gathering (Colledge, 1998; Willcox et al., 2008; Fuller et al., 2011b). The total potential weed flora of rice is vast with ~1800

species reported as modern rice weeds in Asia (Moody, 1989). However, more widespread taxa, and those which are likely to be useful as archaeobotanical indicators are fewer. A survey of agromonic literature on the weeds of rice cultivation in India suggested that weed assemblages of different rice cultivation regimes form differing polythetic sets from among 62 more genera (Fig. 2). While some species or genera are common to all systems, such as *Echinochloa* spp., wild *Oryza* spp. and *Cyperus* spp., others differ. For instance, the grass *Chloris barbata* O. Swartz can be found with upland rice but is unlikely to thrive in a wetter environment (Noda et al., 1985; Thompson, 1996: Table 32, Moody, 1989); this is also true of numerous dicotyledonous taxa. Some sedge taxa, such as the genus *Cyperus* are ubiquitous, but others such as *Eleocharis* are restricted to wetter and irrigated systems, while *Fimbristylis* spp. are excluded from deeply flooded rice. Other taxa are restricted to deeply flooded systems such as Pontederiaceae (e.g. *Monochoria* spp.). Presence of the seeds of some dicot taxa, such as *Spilanthes iabadicensis* A.H. Moore (syn. *S. acmella* auct. pl.) in archaeobotanical samples from Thailand has been taken to indicate dry forms of cultivation in later prehistory (Castillo, 2011). Archaeobotanical evidence in northern India shows that seeds of dry weeds predominate in earlier (Neolithic phases), while wet weed taxa diversify and become more ubiquitous in later periods such as the Iron Age (Fuller and Qin, 2009). Modern ecological and archaeobotanical studies indicate that weed floras associated with rice in archaeological contexts can provide information about ancient cultivation systems.

Phytoliths have preservational advantages in some environments, are easily collected from archaeological sites and can provide an additional proxy alongside seed assemblages (macroremains) or other microfossils (e.g. pollen) in archaeobotanical research. While the identification of plant parts, notably from rice, as well as weeds, has been used for identifying crop-processing stages for rice (Harvey and Fuller, 2005), we focus here on assemblages as representative of local ecosystems, of which the cultivated habitats are expected to dominate. While crop-processing can be expected to filter phytolith assemblages concentrating or reducing the presence of some forms, the starting assemblage for crop-

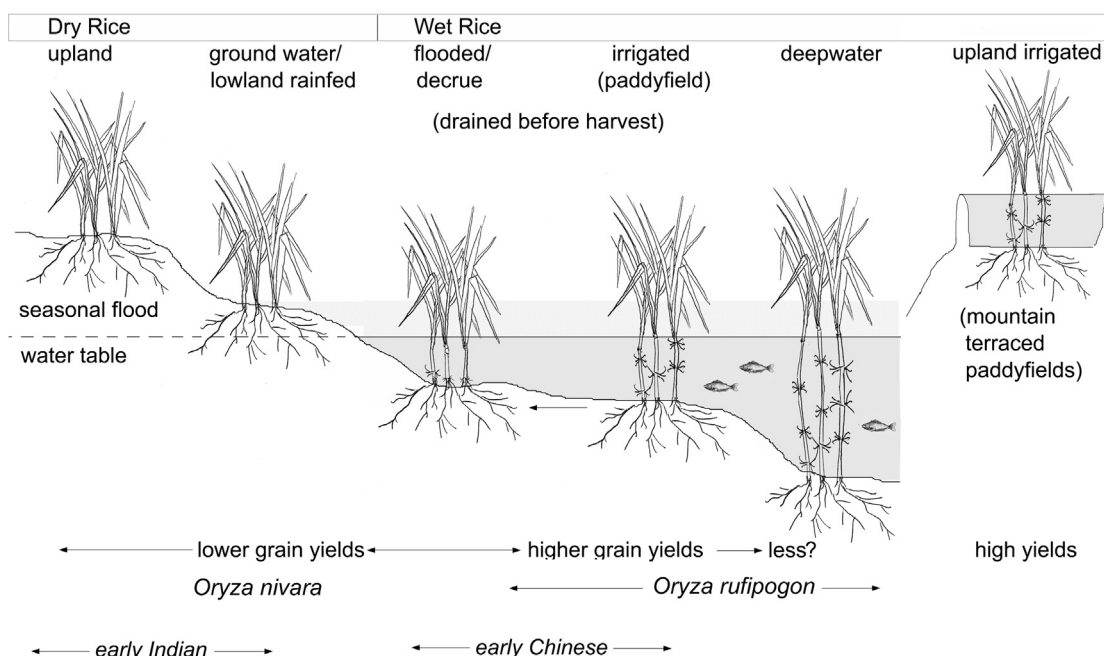


Fig. 1. Rice cultivation systems.

	<i>Polygonum</i>	*																														
	<i>Arundinella</i>		*																													
	<i>Sida</i>	*																														
	<i>Hydrilla</i>																															
	<i>Nepentha</i>			*																												
	<i>Mimosa</i>	*																														
	<i>Aeschynomene</i>																															
	<i>Phyllanthus</i>		*																													
	<i>Euphorbia</i>																															
	<i>Nymphaeoides</i>						*																									
	<i>Scirpus</i>	*						*																								
	<i>Fimbristylis</i>	*																														
	<i>Eleocharis</i>																															
	<i>Cyperus</i>	*	*											*																		
	<i>Maritima</i>	*																														
	<i>Cynotis</i>		*																													
	<i>Commelina</i>						*																									
	<i>Ipomoea</i>	*					*																									
	<i>Tridax</i>																															
	<i>Synedrella</i>	*	*																													
	<i>Emilia</i>	*	*																													
	<i>Eclipta</i>	*																														
	<i>Cuscutaphidum</i>	*																														
	<i>Bidens</i>	*																														
	<i>Ageratum</i>	*	*																													
	<i>Cenell</i>	*																														
	<i>Psilochitum</i>																															
	<i>Celastrus</i>	*					*																									
	<i>Amaranthus</i>	*	*																													
	<i>Trianthema</i>	*																														
	<i>Mollugo</i>	*	*																													
Upland rain-fed																																
Lowland irrigated																																
Deepwater																																

	<i>Melochia</i>	*																														
	<i>Scorpiaria</i>	*																														
	<i>Usonnetia</i>	*																														
	<i>Isonetes</i>	*																														
	<i>Oenanthe</i>																															
	<i>Borreria</i>	*																														
	<i>Portulaca</i>	*																														
	<i>Eichornia</i>	*																														
	<i>Setaria</i>	*																														
	<i>Penicetum</i>																															
	<i>Paspalum</i>	*																														
	<i>Paspalum</i>	*																														
	<i>Panicum</i>	*	*																													
	<i>Oryza</i>	*																														
	<i>Lepidochloa</i>	*																														
	<i>Lernia</i>	*	*																													
	<i>Ischaemum</i>	*																														
	<i>Imperata</i>	*																														
	<i>Eragrostis</i>	*																														
	<i>Eleusine</i>	*																														
	<i>Echinochloa</i>	*																														
	<i>Digitaria</i>	*																														
	<i>Dactyloctenium</i>	*																														
	<i>Cynodon</i>	*																														
	<i>Cyperis</i>	*																														
	<i>Cala</i>	*																														
	<i>Chrysopogon</i>	*																														
	<i>Chimachne</i>	*																														
	<i>Clorid</i>	*	*																													
	<i>Brachiaria</i>	*	*																													
	<i>Ayrtisia</i>	*																														
Upland rain-fed																																
Lowland irrigated																																
Deepwater																																

Fig. 2. Weeds occurring in upland rainfed, lowland irrigated and deep water rice fields.

processing is that from the harvested field. Thus we expect a signature representative of the field's ecology to persist through harvesting and processing to that incorporated into the archaeobotanical record. Phytoliths from some plant taxa, in particular rice, but also potential rice weeds like sedges and panicoid grasses can be identified, although species level identifications are rarely possible. By adopting a statistical approach for the comparison of phytolith assemblages (see below) we established that a finer taxonomic resolution (i.e. beyond genus) is not necessary.

Other studies have shown that statistical patterning of data in phytolith assemblages may be related to distinct environments or ecological zones (Powers-Jones and Padmore, 1993; Bremond et al., 2005; Lu, 2006). We have therefore carried out modern analogue studies to establish the expected phytolith assemblage differences between different rice ecosystems as a basis for interpreting the distinctions between archaeological assemblages.

In this paper we report the patterning of data in modern soil phytolith assemblages from different rice systems, both cultivated and wild, from an initial analysis of nine rice fields. We detail our methods for field sampling of modern analogues and multivariate analysis of soil phytolith assemblages. These patterns highlight the potential to use phytolith assemblages, consisting of both taxonomically identifiable morphotypes and non-taxonomic morphotypes, as proxies for inferring the ecological context of cultivated or wild rice. In addition, we present an archaeological analysis which demonstrates how such data patterns can be utilised for differentiating past cultivation systems. In particular we contrast early agricultural systems in Neolithic northern India and China (Fig. 3), archaeological sites and regions in which phytolith results can be seen to be congruent with other lines of evidence, including macro-remains, for very different forms of early cultivation (see Fuller and Qin, 2009).

2. Field survey and sampling in India

We began with a systematic survey of crop weeds currently growing in a range of rice agricultural systems from western Maharashtra and Orissa in India, which are discussed here, as well as collecting sediments from the same fields for phytolith extraction (Table 1, summarizes a partial dataset used for preliminary analysis). We have also conducted surveys in China (Shandong), Thailand and Laos. We selected fields cultivated using traditional methods, avoiding modern pesticides, weed killers and fertilisers; the focus is on variation in rice weed assemblages so fields that have been treated using industrial cultivation techniques,

especially herbicides, are less useful. We aimed to sample a spectrum of different cultivation regimes (farmer planted *Oryza sativa*), as well as wild rice stands (unplanted *Oryza nivara* or *Oryza rufipogon*), ranging in elevation and water depth conditions (Fig. 4). Between six and twelve samples of around 20 g of topsoil were collected at points in transects across the fields including a proportion from the bunds and field edges as well as from within the fields. Once a sediment sample had been taken the plants within a metre square of the sediment collection point were surveyed and their abundance scored; 1 for one plant, 2 for a few, between 2 and 5; 3 for abundant, more than 5 within a square metre. Individual plant specimens were collected for the project reference collections; whole plant, seeds (if available) and leaves, culms and seeds to process for phytoliths. To the extent possible, plants were taxonomically identified in the field, these and unidentified specimens were subsequently checked in the UCL archaeobotany laboratory against published keys and flora treatments (research which is ongoing).

2.1. Phytolith references from modern plant material

Phytoliths were extracted from the husk/inflorescence, leaf, and culm from each collected plant as well as other plant parts if available, for example *cucurbit* rind. The vast majority of identifiable phytolith references are from monocotyledons, such as grasses, sedges, palms and Commelinaceae (Fig. 5). In addition, phytoliths from dicots, gymnosperms and ferns have also been extracted despite being less diagnostic in many cases. The aim is to create phytolith and seed references for all the species collected from the fields. All the reference samples have been dry ashed at 550°C for 3 h and mounted on slides in Entellan. Some have also been prepared as spidograms. This method keeps sections of the plant part intact in order to clarify where the phytoliths are formed in relation to the anatomy of the plant and each other (Kaplan et al., 1992). After preparing to slide the reference samples are photographed using a Nikon Cool Pix camera at 200× magnification. This provides the clearest images while identifiable characteristics were still plainly visible.

2.2. Phytoliths from field sediments

Phytoliths were extracted from around 800 mg of sediment per sample using the standard protocol at the Institute of Archaeology, UCL (Rosen, 1999). Once processed to slide between 300 and 400

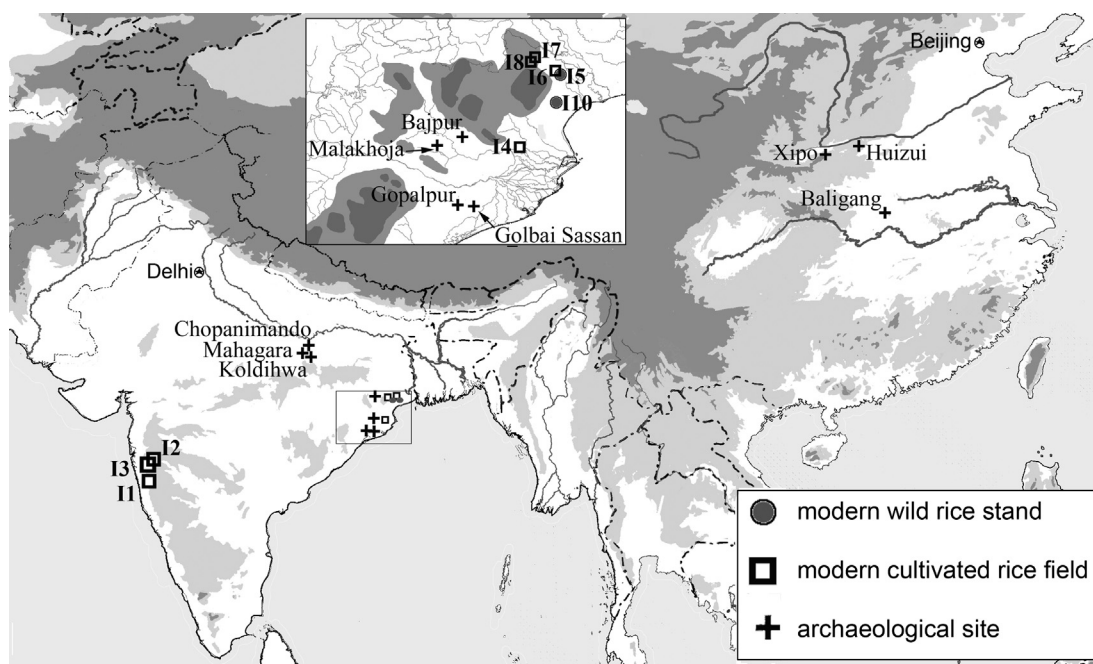


Fig. 3. Map of sites sampled and analysed.

single cells and 100–200 multicells or silica skeletons were counted under a Leica transmitted light microscope at 400× magnification.

2.3. Identification

Where the identification criteria were clear, phytolith morphotypes were identified to family, sub-family or genus level using the reference collection created for this project as well as existing comparative reference collections at UCL (Weisskopf, 2010). Recent work on identifying phytoliths from Commelinaceae (Eichhorn

et al., 2010) also proved invaluable. In addition we used Kealhofer and Piperno's photographs of phytoliths from Southeast Asian Flora (1998). The ICPN procedure for naming phytoliths (Madella et al., 2005) was used as well as anatomical descriptions (Metcalf, 1960).

3. Statistical analysis

Canonical correspondence analysis was selected as the multivariate technique most appropriate for analysing these data. It graphically displays the relationship between the samples and

Table 1

Modern rice stands in India sampled for weeds and phytoliths, included in the preliminary studies reported here.

Site No.	GPS NW corner	Elevation	Field area (approximate)	Soil type	Cultivation type	Planting date/approximate harvest date	Rice variety
I1	N17°45'23.3 E73°24'50.3	40 m	6 m × 10 m	Red, iron rich, sandy	Lowland rainfed, bunds	Nearly mature	Subspecies <i>indica</i>
I2	N18°20'44.1 E73°32'01.8'	655 m	20 m × 8 m (Curved)	Red tropical soil, somewhat lateritic	Rainfed upland, transplanted	About to flower/flowering	<i>Tropical japonica/indica</i> hybrid (?), slight awn
I3	N18°20'15.5 E73°27'16.5'	693 m	30 m × 10 m	Colluvial from lateritic soils brown	Rainfed upland, broadcast, along small river	About to flower/flowering	Uncertain: <i>indica/japonica</i> ?
I4	N20°48'04.1' E86°09'15.4'	18 m	20 m × 30 m	Alluvial plain	Lowland, rainfed	Harvesting now (03/10/10)	Subspecies <i>indica</i>
I5	N22°1'35.9 E86°40'38.1	59 m	10 m × 40 m	Red acidic sandy soil	Uncultivated, seasonally flooded during monsoon area standing water in puddles	Some shattering, flowering & green immature spikelets	Annual wild rice (<i>O. nivara</i>)
I6	N22°1'40.2 E86°40'31.8	59 m	40 m × 40 m	Red acidic sandy soil	Lowland, rainfed	Some in flower	Subspecies <i>indica</i>
I7	N22°10'49.0 E86°28'15.1'	333 m	20–30 m × 70 m	Upland (mountains N. Orissa)	Decrue: Shallow (no standing water) to deep water (~1 m) rice, sown when tank is low, around edge of stream fed pond/tank.	Planted June (1st wk) Harvest end of Nov	Subspecies <i>indica</i> (?). Cultivated by Munda tribal population.
I8	N22°10'44.2 E86°28'13.0'	335 m	20 m × 50 m	Upland (mountains N. Orissa)	Decrue: shown in stream, bed with standing water; shallow (~5 cm) and variable water depth at time of collection.	Planted June (1st wk) Harvest end of Nov	Subspecies <i>indica</i> (?). Cultivated by Munda tribal population.
I10	N21°46'53.7 E86°39'17.5'	55 m	30 m × 10 m	Clayey, over red sandy colluvium and alluvium	Pond fed by stream and irrigation overflow	Most flowering, some green	Perennial wild rice (<i>O. rufipogon</i>)

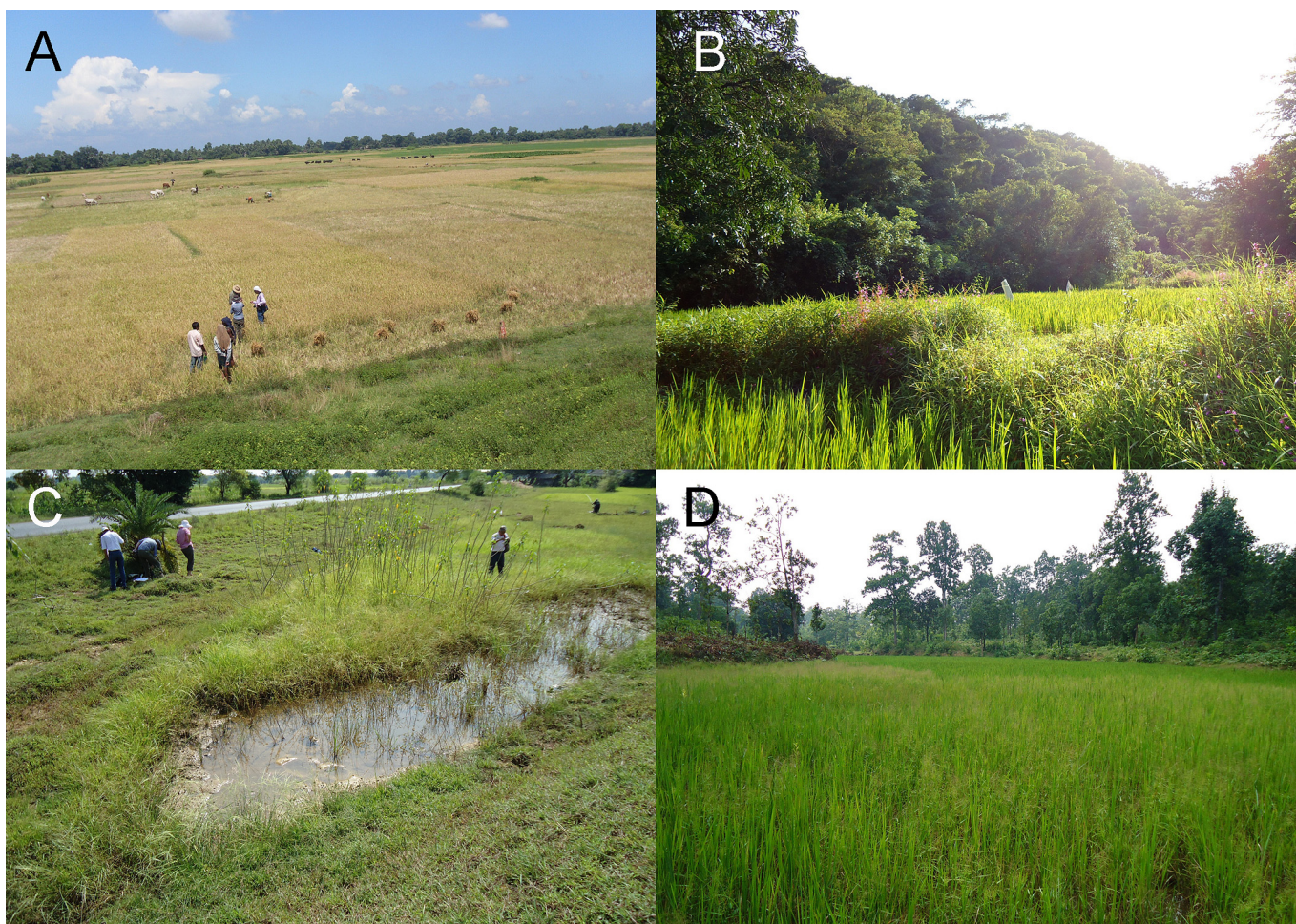


Fig. 4. Rice fields, A. Lowland rainfed, B. Upland rainfed, C. *Oryza nivara*, lowland rainfed wild annual, D. Decrue.

variables (in this case phytolith morphotypes) highlighting combinations of clustering and seriation (Høilund-Neilson, 1988:30, Colledge, 2001:67) so morphotypes will be closer to samples in which they are more abundant (Powers et al., 1989:321). Here it has been used to describe sample-to-sample, morphotype to morphotype, and the coincidence of morphotype to sample relationships in order to interpret why these distributions occur, in this case to establish patterns arising from the proportions of morphotypes in samples from each arable system. CANOCO software, devised by ter Braak (1988) was the programme used to carry out the correspondence analysis on the data. CANADRAW, developed by Smilauer (1992), was used to generate ordination diagrams showing correspondence between samples and phytolith morphotypes.

3.1. Morphotype classification

Multivariate analyses involved a process of normalising the total dataset to retain those variables that could differentiate the samples and aid inference. Although they were identified and counted, some phytolith morphotypes, indeterminate, sheets, hairs, stomata and tracheid forms, were removed from the dataset before Canoco analysis as these were not expected to provide relevant information. The remaining morphotypes were grouped into broader categories (Table 2).

While it is often a challenge to identify phytoliths to genus or species level some morphotypes can be used to indicate a group of

plants with similar characteristics or environmental requirements. Some are common to a wide range of plants but can be grouped according to sub-family. For example different Poaceae subfamilies produce morphologically varied phytoliths (Twiss et al., 1969; Twiss, 1992; Iriarte and Paz, 2009). Panicoideae, many of which grow in warm humid conditions (although a few persist in cool and dry habitats), produce bilobate, polylobate and quadra-lobate shaped short cell phytoliths. Chloridoideae, which indicate warmer and usually drier habitats, produce short saddles. Bambusoideae produce collapsed saddles and indicate a sub-tropical – tropical environment (Lu et al., 2002:382, Twiss et al., 1969; Piperno and Pearsall, 1998; Piperno, 2006). Plants belonging to the Oryzeae tribe, for example, *Leersia* (Solander ex Swartz, Prodr.), can produce scooped bilobes (Pearsall et al., 1995; Harvey and Fuller, 2005; Weisskopf, 2010) and are often distributed in seasonally inundated wetlands (Clayton and Renvoize, 1986; Vaughan, 1994), so are a good indicator of local environments. High proportions of bulliform shaped phytoliths can be linked with hydrophilic grasses and increased evapotranspiration (Delhon et al., 2003:179, Webb and Longstaffe, 2002, 2003). These were grouped with other indicators such as diatoms and sponge spicules expected in wetland or submerged conditions, (Imsieke et al., 1995; GistGee, 1931), although some diatoms and sponge spicules are specific to soils (Wilding and Drees, 1968; Pearsall and Piperno, 1993:97). For the purposes of the present analysis all diatoms were treated together, but further investigation of diatom taxonomy and ecology could repay future research.

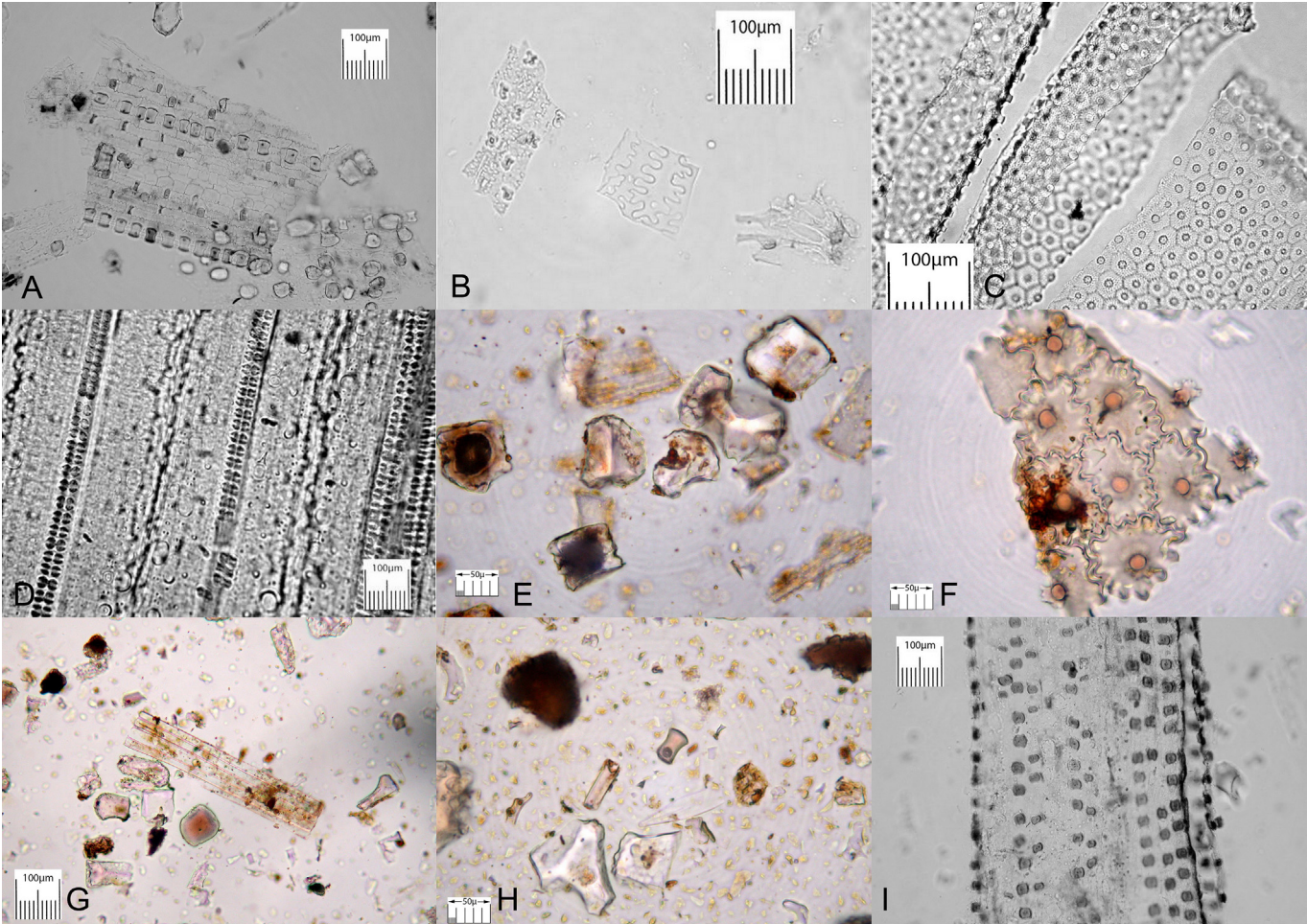


Fig. 5. Phytoliths, left to right from top left corner: A. *Bambusa* sp., leaf-culm, ashed bund decrue; B. *Brachiaria* sp., edge upland fields, ashed; C. *Cyperus pilosus*, deep water, leaf clearing; D. *Leersia hexandra* leaf transplanted paddy edge, leaf clearing; E. Bulliforms, upland river valley; F. *Cyperaceae*, lowland rainfed; G. Diatom, two tiered, bulliform, rufipogon; H. Diatoms, platey, upland decrue; I. *Chloris virgata* leaf, bund edge upland field ashed.

4. Results

Our field surveys of rice stands in India revealed a wide range of non-rice, or “weed” diversity, including about 60 species. These observations are summarized in simplified form in Table 3. In general, the number of weeds and the number of weed species was higher in dry fields and lower in deep water conditions. Thus perennial wild rice, *O. rufipogon*, averaged 14 weed taxa (from 9 to

16). These were most often dominated by sedges (*Cyperaceae*), with dicotyledons and panicoid grasses also frequent. Other grasses (apart from *Oryza* spp.) were largely absent and *Commelinaceae* were rare. The highest diversity was found amongst rainfed (dry) rice, which averaged 31 weed taxa per field (from 26 to 45). Amongst these fields dicotyledonous weeds were usually the most frequent, numerous and diverse. Panicoid grasses and *Commelinaceae* were also quite common, and a few species of sedges could

Table 2
Categories of phytolith morphotypes used for correspondence analysis.

Oryza	Cyperaceae	Hydrophilic species	Panicoid	Other and indeterminate Poaceae	Dicotyledon	Arecaceae	Commelinaceae
Oryza glume	Long rods	Bulliform	Bilobate	Long smooth	Smooth spheroid	Globular echinate	Two-tiered
Oryza bulliform	Cones	Cuneiform bulliform	Polylobate	Long sinuate	Platey		Multi-tiered
Leaf/culm cf Oryza	Cyperaceae leaf	Scooped bilobate	Cross	Long dendritic	Single polyhedron		
cf. Oryza husk	Cyperaceae husk	Crescent (equisetum)	cf. Setaria bilobate	Crenate	Scalloped		
		Leaf/culm Phragmites	Leaf/culm bilobate	Rondel	Single jigsaw		
		Leaf/culm reed	Leaf/culm cross	Stipa rondel	Leaf/culm jigsaw		
		leaf/culm square-cell	cf. Setaria husk	Saddle	Polyhedral hairbase		
		Diatoms	cf. Panicum husk	Collapsed saddle	Multi Polyhedrons		
		Sponge spicules	Millet type 1	Elongate			
			Millet type 2	Indeterminate Leaf/culm			
				Leaf/culm saddle			
				Leaf/culm long cells			
				Indeterminate husk			

Table 3

Tabular summary of diversity and dominance of weed taxa encountered in rice stand surveys. Species are grouped into broad taxonomic categories that are more comparable to phytolith data. Fields are arranged from left to right on a scale from dry to wet conditions. Letters indicate rank order dominance in terms of frequency within the field. A = most frequent, G = least frequent, 0 = entirely absent. Numbers in brackets indicate the diversity within each category (i.e. the number of species). Total number of weed species recorded for each field is indicated at the bottom. This total number may include categories not otherwise shown, such as ferns or grasses which could not be classified.

Characterisation of rice stands	Dry Cult.	Dry Wild	Dry Cult.	Dry Cult.	Dry Cult.	Dry Cult.	Dry Cult.	Wet Cult.	Wet Cult.	Wet Cult.	Wet Wild	Wet Wild	Wet Wild	Wet Wild
Field number	I6	I5	I1	I2	I3	I7 west	I4	I8	I12	I7 east	I10	I9	I13	I11
Dicotyledons	A [29]	B [9]	A [17]	A [14]	A [16]	A [21]	A [16]	A [19]	A [6]	A [4]	B [6]	B [5]	A [6]	D [3]
Panicoids	B [7]	C [6]	B [2]	B [8]	C [3]	B [4]	C [2]	D [3]	B [3]	B [3]	C [2]	D [2]	0	B [3]
Chloridoids	E [2]	D [2]	0	F [1]	D [2]	E [1]	F [1]	F [2]	0	0	0	0	0	F [1]
Pooids	0	G [1]	0	0	0	0	0	G [2]	0	0	0	E [1]	0	0
Cyperaceae	D [3]	A [5]	F [1]	C [2]	F [2]	C [4]	E [4]	C [3]	C [3]	0	A [3]	A [5]	C [1]	A [5]
Commelinaceae	F [2]	E [1]	C [4]	E [1]	E [2]	0	B [2]	E [3]	0	D [1]	E [1]	F [1]	0	E [1]
Other Monocotyledons	C [2]	G [2]	0	D [1]	B [2]	E [1]	D [1]	B [3]	0	C [1]	D [1]	D [2]	B [1]	D [2]
Total weed taxa	45	26	28	27	31	31	26	35	12	9	15	16	9	15

be highly numerous (especially *Fimbristylis* spp. and *Cyperus* spp.). Chloridoid grasses, such as *Eragrostis* or *Cynodon* were recurrent low frequency weeds in dry rice. A few ferns occurred in rainfed upland rice in western India. Annual wild rice, *O. nivara*, had a generally similar assemblage to dryland rice, with 26 weed taxa, although sedges were the most common associated taxa, followed by dicotyledons and panicoid grasses. Although full details of the modern weed survey data is beyond the scope of the present paper, the summary by broad taxonomic categories in should facilitate comparison to phytolith data.

Using correspondence analysis, the phytolith assemblages were grouped according to site and field system (Fig. 6). The chart shows samples analysed so far from the sites and systems in India. There is some division between east and west India. All the sites from the Western Ghats appear in the upper quadrants. The rainfed transplanted rice field and rainfed river valley field, which were both much higher than the lowland rainfed sites, correspond very closely, suggesting local environment, and elevation, also have strong influences on the weed flora. The closest corresponding system from Orissa, a *décrue* field, with shallow to deep water is also from an upland setting. The samples collected from the shallow end of this field correspond more closely with the Western Ghat rainfed sites, which have higher rainfall. The sample from the deep water corresponds to samples from a second field of *décrue* rice growing nearby.

Two wild rice fields were sampled, one (*O. nivara*) on an uncultivated patch between the road and an irrigation canal. There were puddles but the rice was not inundated. The other (*O. rufipogon*) grows in deeper water and the makeup of these samples is very similar to the upland *décrue* cultivated rice, although with less differentiation between samples, so it may be a challenge to unpick them. The *O. nivara* field was only a few metres away from a cultivated lowland rainfed field, yet all the samples from these two adjacent sites are separated in the correspondence analysis, suggesting the proportions of phytolith morphotypes in the samples differentiate rainfed wild and cultivated populations. Similarity was found in a single bund sample, but not in the actually cultivated context. The two lowland rainfed samples from Orissa are distinct on the basis of correspondence analysis. They are at different elevations, the first was on the alluvial plain (18 m elevation), while the other was higher (59 m). The lowland rainfed sample from Maharashtra is also separate from the other lowland rainfed samples.

The phytolith assemblages were also classified into 8 groups, *Oryza*, Cyperaceae, hydrophilic species, Panicoideae, other Poaceae, dicotyledon, Palmae, and Commelinaceae (Table 2). *Oryza* is rare at all sites and only shows in one pie chart from the lowland rainfed sample in the alluvial plain in Orissa (Fig. 6B). This is not surprising at the cultivated sites as rice is harvested and removed but more might have been expected in the sediments from the uncultivated

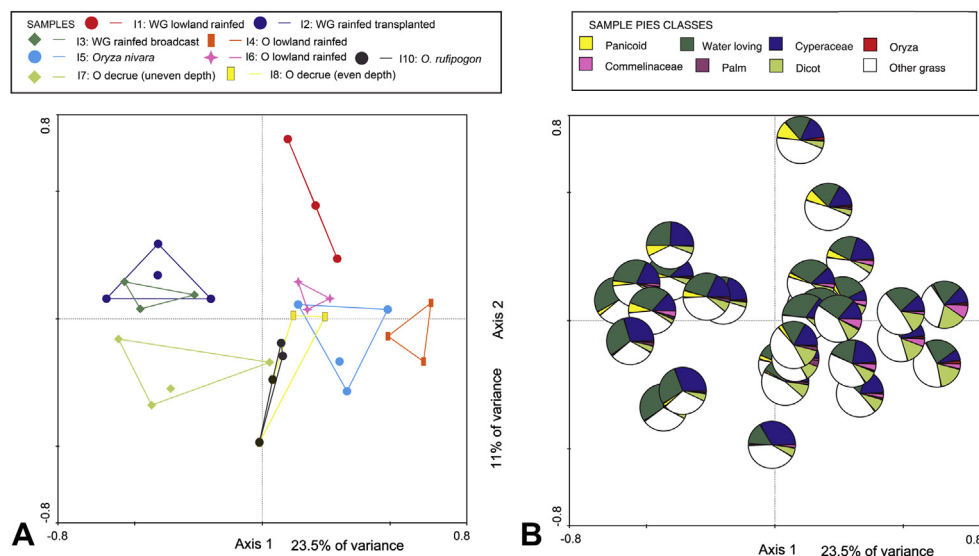


Fig. 6. Correspondence analysis of phytoliths from modern Indian fields: A. Field types, B. Pie charts showing the constituents of the samples.

fields. The rainfed samples from the hills in the Western Ghats had quite high proportions of hydrophilic morphotypes, as well as Cyperaceae with few dicotyledons some Commelinaceae and Arecaceae. All the sites in Maharashtra contained phytoliths from Panicoid grasses, especially the samples from the lowland rainfed site, in contrast to the samples from Orissa, where panicoids were insignificant in many samples. A major difference between the lowland rainfed fields in Orissa is the presence of panicoids in the higher fields and absence in the field on the alluvial plain. Dicotyledons seem more significant in the Orissa sites, in particular the lowland rainfed site from the alluvial plain. The samples from this site have fewer hydrophilic species morphotypes and Cyperaceae but *Commelina* is more significant. Both wild rice stands have high proportions of wild grass. The *O. rufipogon* site has quite high levels of Cyperaceae and is the only site to have *Arecaceae* in several samples. The upland décrue field has high levels of morphotypes from hydrophilic species (see Inline Supplementary Table S1).

Inline Supplementary Table S1 can be found online at <http://dx.doi.org/10.1016/j.jas.2013.04.026>.

5. Cultivation in Neolithic China and India

5.1. Chinese archaeological samples

The Chinese samples come from Neolithic central China, Henan province. These come from Huizui, a site in the Yilou River Valley, a tributary of the central Yellow River, and Xipo, which is further north and west but still in the central Yellow River Valley, as well as Baligang in southern Henan, on a northerly tributary of the Yangtze watershed. The samples analysed here date from the Middle to Terminal Neolithic (6900 BP–3850 BP), Yangshao to Late Longshan in the Yellow River sequence.

These sites straddle the Qinling Mountains, the division between the Yellow and Yangtze watershed and also the conventional dividing line between the Neolithic northern millet-based economies and southern wet rice agriculture (Li, 1983:22, Barnes, 1999:97). Above this line winters are cold and there is limited precipitation. The staple crops are herbaceous, heliophilous, and mostly annuals of open grassland (Ames, 1939:8, Li, 1983:22–3). The ecological setting of the Central Plains, dry cold winters, infertile loess soils retaining little water, has meant crops chosen in these areas tend to be plants that can thrive in drought conditions and have a short growth period before harvest, such as millets (Yan, 1992:115). The earliest main staple cultigens, during the Neolithic in North Central China were millets (Li, 1983:53) *Panicum miliaceum* (2 kinds, glutinous and non-glutinous) and *Setaria italica*, both meeting these requirements (Lu, 2006: 61,129, Yan, 1992:115 Li, 1983:29).

Rice (*O. sativa*) arrived in North China later than local millet cultivation, presumably spreading from origins to the south by ca. 6000 BP (Fuller et al., 2010). It is generally supposed that contact between northern dryland farmers and southern wetland farmers is most likely to have occurred in Henan (Li, 1983:54).

Rice is present at many Yellow River Valley sites during the Neolithic period, and with increasing presence from the Middle and Late Yangshao periods. This is clear from systematic regional studies of macro-remains such as in the Yilou (Lee et al., 2007) and the Ying (Fuller and Zhang, 2007). However, the millets, *Panicum miliaceum* and, to a greater extent, *Setaria italica* remain the predominant cereal crops in the Yellow River Valley sites discussed here. In contrast to sites in northern Henan, rice was the most common crop at Baligang in the Nanyang basin, southern Henan, (Fuller unpublished data; cf. Fuller and Zhang, 2007). There is evidence suggesting paddy farming (Weisskopf, 2010), which continued from earlier Neolithic systems of wet rice farming that

are evident in the Middle Yangtze by 4500–4000 BC and in the Lower Yangtze by around 4000 BC (Fuller and Qin, 2009; Fuller et al., 2011b; Nasu et al., 2011).

5.2. Indian archaeological samples

Indian archaeological samples were collected from sites in the Belan Valley (Uttar Pradesh), and the coastal plain of Orissa. 3 sites in the Belan Valley, north India, were sampled: Chopani-Mando, Mesolithic (10,000–3500 BC), Koldihwa, Neolithic to Iron Age (1900–500 BC) and Mahagara, Neolithic (1700–1400 BC). Samples were collected from new test pits and section clearance but could be related to previous recorded stratigraphy of the 1970s University of Allahabad excavations (Sharma and Mandal, 1980). The archaeobotanical sampling and results from these sites have been discussed elsewhere (Harvey et al., 2005; Harvey and Fuller, 2005; Harvey, 2006; Fuller, 2006). Four sites were sampled for phytoliths alongside macro-remains in Orissa (Harvey et al., 2006). They were selected to represent the Neolithic/Chalcolithic period but often show evidence for occupation through the Iron Age. Two artefactually and archaeobotanically poorer upland sites from central Orissa, Bajpur and Malakhoja, both date to the Second Millennium BC but lack radiometric dating evidence to confirm this, and Gopalpur and Golbai Sasan, two lowland settlement mound sites with rich artefact and macrobotanical evidence. These sites were sampled by cleaned exposed and eroding stratigraphic section through a narrowly stepped trench. While these sites are thought to date from ca. 2500 BC to ca. 1000 BC (Harvey et al., 2006), macrobotanical analyses and direct AMS dates on crop remains suggest samples derive mainly from slumped strata from the later phases of the sites, with dates from 1300 to 1000 BC at Golbai Sasan and 1400 to 1000 BC at Gopalpur (Harvey, 2006). Samples therefore essentially reflect the developed agricultural economy at the end of the Neolithic (Chalcolithic) and the transition to the Iron Age. These two sites produced macro-remains dominated by evidence for rice cultivation, as well as pulses, while evidence for cultivation in the upland sites remains ambiguous.

5.3. Results

A canonical correspondence analysis of all archaeological samples was carried out (Fig. 7). Within this analysis a simpler initial classification for grouping morphotypes was used which included, rice (*Oryza*), millet, hydrophilic species, Poaceae husk, Poaceae leaf and Arecaceae, with all others considered unclassified. Axis 1 showed 28.1% of variance with a clear separation between the Indian and Chinese samples. The samples with rice from both regions are closer towards the centre of the chart, although mostly separate along both axes. There is 12.8% of variance on Axis 2. Among Chinese samples, samples from sites with millet fall on the upper portion of Axis 2, while among Indian samples, sites without with evidence for rice or indeed any crops fall at the lower end of Axis 2.

5.4. Comparison of phytoliths assemblages from Indian and Chinese sites

The major differences are seen in the four quadrants. The millet crops (*Setaria italica* and *Panicum miliaceum*) are clear in the Yellow River Valley samples but are absent from the Indian. Chinese samples contain rice alongside phytolith morphotypes from hydrophilic species, whereas the Indian samples in the top left quadrant have high proportions of rice but mostly accompanied by Poaceae husk, suggesting rainfed cultivation systems. The samples from these Indian sites had very low levels or no phytoliths from hydrophilic species. The Chinese samples in the right lower

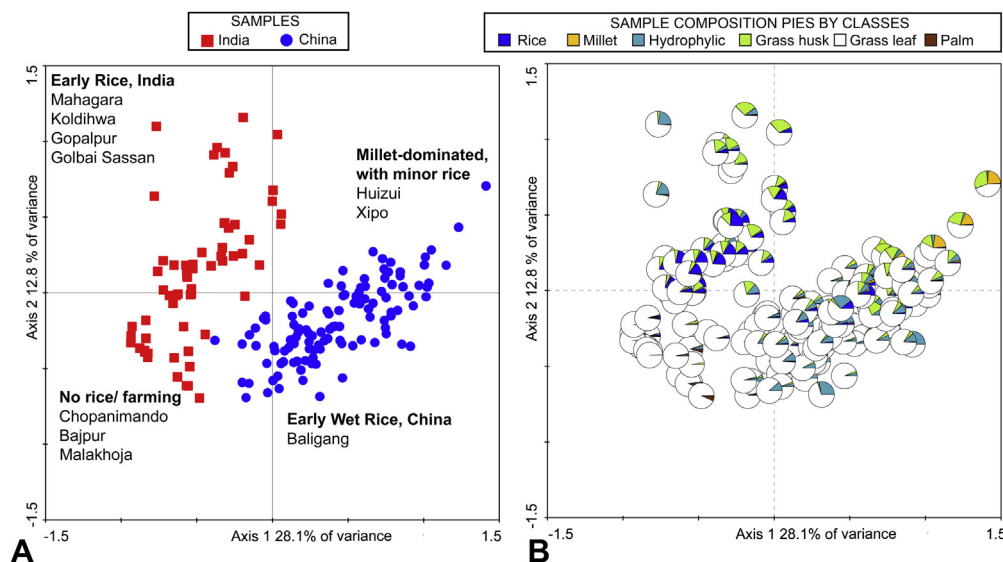


Fig. 7. Archaeological samples, A. Correspondence analysis of phytoliths comparing Indian and Chinese archaeological sites, B. Pie charts showing the constituents of the samples.

quadrant have relatively large proportions of hydrophilic species, indicative of wet rice farming. This suggests a separation of dry versus wet farming along axis 2. The lower left quadrant shows the Indian samples made up of wild *Poaceae* and *Arecaceae*. These are from Mesolithic and upland sites and demonstrate no evidence of agriculture (see Inline Supplementary Table S2).

Inline Supplementary Table S2 can be found online at <http://dx.doi.org/10.1016/j.jas.2013.04.026>.

6. Conclusions

This paper reports a new approach to reconstructing early Asian rice ecosystems, including distinguishing wild gathered rice from cultivated rice, and flooded paddy field rice systems, the conditions under which rice grew and its implications for cultivation practices. This works through use of the weed flora composition associated with rice as an index of field conditions. In the present case we have extended the weed flora approach to use of phytolith assemblages, which include both taxonomically diagnostic phytoliths and non-diagnostic phytolith morphotypes. Even amongst diagnostic forms, species level identification is rarely possible, and our analyses indicate that this is not necessary to provide ecological information. The overall quantitative comparisons of phytolith morphotype data appear to include enough systematic variation to be able to reconstruct differences between rice systems. This phytolith assemblage approach has a number of advantages. First, phytoliths have preservation advantages over carbonized macro-remains in many tropical contexts (Piperno, 1995:130) and as such may be more easily collected from small-scale excavations, section cleaning, etc. Second, the assemblage approach means that it is not necessary to be able to resolve the taxonomy of phytoliths to lower taxonomic levels, such as genus and species, which is likely to prove impossible for the majority of phytoliths. This is not meant to deny the importance of expanding taxonomic reference collections for phytoliths, which has also been part of our analogue studies. Also, we maintain phytolith analysis should be used in conjunction with macro-remains which can provide evidence for other crops not represented here (e.g. pulses, oilseeds, fruits), for providing potential species level identification for some weeds, especially amongst dicots (e.g. Castillo, 2011), and by providing definitive evidence on the domestication status of rice through spikelet bases (e.g. Fuller et al., 2009). Fully integrated statistical

analyses that include both phytoliths and macro-remains from the same sites and contexts still require development, a challenge due to different quantification methods and sample sizes.

Previous overviews of the development of early rice cultivation have often been more conjectural than evidential. For example, Gorman (1977) proposed that early rice cultivation started in the Southeast Asian uplands and later spread to the lowlands, whereas White (1989) proposed a beginning in lowland floodplains with later adaptation to the uplands. Within the context of Southeast Asia both systems may be early and represent different trajectories of rice dispersal from China rather than local domestication (Castillo and Fuller, 2010). Current evidence points to dispersal of domesticated rice from the Yangtze, where early systems were focused on alluvial lowlands and management of water regime of what was initially a perennial wild rice (Fuller and Qin, 2009; Fuller et al., 2010). While the current archaeobotanical record provides sufficient data for charting the first appearance of rice over large areas (Fuller et al., 2010, 2011a), inferring how rice was cultivated and how these methods changed is based on many fewer empirical data points. The phytolith assemblage approach outlined here has the potential to rapidly improve and expand the empirical evidence for how rice was cultivated at particular times and places. Already our archaeological results suggest that most early systems in China were wet-rice paddy field systems, which spread northwards from the Yangtze valley from the Yangshao period onwards (as per Fuller et al., 2010). In addition, these data support the hypothesis that early rice cultivation in northern and eastern India was very different from that of China and focused on drier, monsoon-rainfed systems (as per Fuller and Qin, 2009). Although our archaeological dataset included 10 sites, 174 sampled contexts and over 900,000 counted phytoliths, many more samples are needed to better understand the complex early history of rice cultivation.

This work illustrates the potential of phytolith analysis to differentiate agricultural systems on an assemblage level. Such an approach was pioneered in British archaeology by Powers-Jones and Padmore (1993) and has been applied in palaeoecological studies (e.g. Bremond et al., 2005; Lu et al., 2007). The results reported above indicate that different modern field samples from India are grouped and separated logically, while archaeological analyses show that we also get separation of different cultural historical entities which makes sense in terms of cultivation systems. This has the further implication that, at least in agricultural

societies, the phytolith assemblage that dominates general samples across archaeological settlement fill and secondary contexts contains a strong signature of agricultural fields, presumably brought onto site by harvest, crop-processing and the recycling of crop-processing residues. Such an approach has potential beyond rice in the study of other agricultural systems.

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